SYSTEM AND METHOD OF COMMAND SIGNAL CONDITIONING IN HIGH RESPONSE SYSTEMS

This invention was developed in the course of work under

5   U.S. government contract MDA972-99-9-0003. The U.S. government may possess certain rights in the invention.

Background of the Invention

The present invention is directed to an improved control

10 system and method and in particular, to a system and method for command signal conditioning in high response systems.

Modern electrically powered motion control systems rely on digital control for operation. Typically, such systems consist of a central digital controller which communicates

15 with one or more motors via corresponding digital motor controllers. The computation or frame rate of the central controller is often much lower than the frame rate of the motor controller. As a result, when the motor controller is highly responsive, the coarse step commands from the central

20 controller can cause significant electrical current oscillations. This in turn can result in wasted energy and increased heat generation.

Existing low frequency-to-high frequency response systems handle excess heat generation by either adding a cooling

25 system or in the case where one already exists, increasing the size or capacity of the existing cooling system, if possible.

Waste energy is typically handled by increasing the size of the power generation system and wiring. In applications involving size or weight constraints, such as in aerospace systems, these solutions are often not acceptable. Such

5   solutions also significantly increase the overall cost and maintenance of the system.

Moreover, any solution to heat generation and waste energy problems must not adversely impact on the phase shift of the system so that the desired response can be maintained.

10   This is especially true in high response systems requiring precise positioning.

The present invention overcomes the foregoing limitations. In accordance with the present invention, the need for a cost-effective control system and method which

15   reduces waste energy and heat generation and minimally affects the size, weight and response of the system is fulfilled.

Summary of the Invention

A control system having a central digital controller

20   having a digital controller frame rate and a command signal, a motor, and a motor controller in communication with the central digital controller and the motor, the motor controller having a motor controller frame rate higher than the digital controller frame rate is disclosed. The control system

25   comprises a signal conditioner adapted to condition the command signal so as to generate a modified command signal at the motor controller frame rate. The signal conditioner comprises a computer readable medium having computer readable program code embodied thereon.

30   In one embodiment, the computer readable code, when executed, calculates a moving average at the frame rate of the motor controller, such that the modified command signal is an

interpolation of the command signal over a plurality of frames. In another embodiment, the signal conditioner comprises a first order hold and a filter in communication with the first order hold. The first order hold comprises a

5   linear extrapolation of the command signal of the digital controller over a plurality of frames. The filter may comprise a first order filter having a breakpoint which is selected to negate any high frequency gain increase introduced by the first order hold. In one embodiment, the linear

10   extrapolation comprises the use of the last two command signals of the digital controller and has a starting point being the most recent command signal of the digital controller. The computer readable medium may be stored on the motor controller.

15   An apparatus comprising a computer readable medium having computer readable program code embodied thereon is also disclosed. The computer readable program code, when executed, implements on a computer a method of conditioning a command signal generated by a central digital controller having a

20   digital controller frame rate prior to its application to a motor controller having a motor controller frame rate higher than the digital controller frame rate. The method modifies the command signal to produce a modified command signal at the motor controller frame rate.

25   In one embodiment, the method of conditioning comprises calculating a moving average at the frame rate of the motor controller such that the modified command signal is an interpolation of the command signal over a plurality of frames. In another embodiment, the method of conditioning

30   comprises linearly extrapolating the command signal from the digital controller over a plurality of frames and filtering the linearly extrapolated command signal.

A control system comprising a central digital controller having a command signal and a digital controller frame rate, a motor controller having a motor controller frame rate higher than the digital controller frame rate, and a signal

5   conditioner adapted to condition the command signal to produce a modified command signal at the motor controller frame rate is also disclosed. The signal conditioner comprises a computer readable medium having computer readable program code embodied thereon. In one embodiment, the computer readable

10 code, when executed, calculates a moving average at the frame rate of the motor controller such that the modified command signal is an interpolation of the command signal over a plurality of frames. In another embodiment, the signal conditioner comprises a first order hold, and a filter in

15 communication with the first order hold. The first order hold comprises a linear extrapolation of the command signal over a plurality of frames. The filter may comprise a first order filter having a breakpoint which is selected to negate any high frequency gain increase introduced by the linear

20 extrapolation. The linear extrapolation may comprise the use of the last two command signals of the digital controller and has a starting point being the most recent command signal of the digital controller. The computer readable medium is preferably stored on the motor controller.

25   A method of conditioning a command signal generated by a central digital controller having a digital controller frame rate prior to its application to a motor controller having a motor controller frame rate higher than the digital controller frame rate is also disclosed. The method comprises

30 conditioning the command signal to produce a modified command signal at the motor controller frame rate. In one embodiment,

the step of conditioning comprises interpolating the command signal over a plurality of frames and in particular, calculating a moving average at the frame rate of the motor controller. In another embodiment, the step of conditioning

5 comprises linearly extrapolating the command signal of the digital controller over a plurality of frames, and filtering the linearly extrapolated command signal. The step of filtering may comprise selecting a breakpoint to negate any high frequency gain increase introduced by the step of linear

10 extrapolation.

Further features and advantages of the present invention, as well as the structure and operation of various embodiments of the present invention, are described in detail below with reference to the accompanying drawings.

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Brief Description of the Drawings

Fig. 1 is a block diagram of a portion of a motion control system in accordance with the present invention;

Fig. 2 is a block diagram of a method of command signal

20 conditioning in accordance with one embodiment of the present invention;

Fig. 3 is a block diagram of a method of command signal conditioning in accordance with another embodiment of the present invention;

25 Fig. 4 is a graph comparing the command signal from the central controller of Fig. 1 in an unconditioned state to the command signal from the central controller of Fig. 1 as processed by the conditioning method of Fig. 2;

Fig. 5 is a graph comparing the command signal from the

30 central controller of Fig. 1 in an unconditioned state to the command signal from the central controller of Fig. 1 as processed by the conditioning method of Fig. 3;

Fig. 6 is a graph comparing the heat load generated at the motor of Fig. 1 under a typical operation cycle using the digital control systems of Figs. 2 and 3;

Fig. 7 is a graph comparing the heat load generated at 5 the motor controller of Fig. 1 under a typical operation cycle using the digital control systems of Figs. 2 and 3;

Fig. 8A is a graph showing the gain of the response of the digital control system of Fig. 3 without the first order filter of Fig. 3; and

10 Fig. 8B is a graph showing the gain of the response of the digital control system of Fig. 3 with the first order filter of Fig. 3.

Detailed Description of the Preferred Embodiments

15 The present invention is directed to an improved control system and method. While the system will be described with respect to a motion control system, it can be appreciated that it can be applied to any high response system. The system, a portion of which is shown in Fig. 1, typically comprises a 20 central digital controller 12 which controls one or more actuator systems 14. Each actuator system includes among other things an electric motor 16 and a digital motor controller 18 for control thereof. The central controller 12 generates an input or command signal which is transmitted to 25 the appropriate motor controller 18 and conditioned in accordance with the present invention.

Conditioning of the command signal is accomplished by using the lower rate data from the central controller to produce a modified command signal at the frame rate of the 30 motor controller 18. In one embodiment of the present invention as shown in Fig. 2, conditioning of the command signal involves interpolation of the command signal over a

plurality of frames and in particular, calculating a moving
average at the frame rate of the motor controller 18 and
adjusting the command signal of the central controller 12
accordingly. This approach will be hereinafter referred to as

5   the moving average approach. While this approach is
preferably implemented in software residing on the motor
controller 18, it can be appreciated that it can be
implemented in software residing on other devices of the
control system or in hardware. The moving average is

10 calculated as follows:

$$(C_M + C_{M-1} + C_{M-2} + \ldots + C_{M+1-N}) / N$$

wherein C_M = the value of the command signal from the central
controller as sampled by the motor controller at a current
point in time;

15 C_{M-1} = the value of the command signal from the central
controller as sampled by the motor controller one motor
controller frame in the past (and so on for C_{M-2}, etc.); and
N = an integer ratio of the motor control frame rate divided

by the central controller frame rate.

20   The quantity of the frames used for the moving average is
equal to the integer value of the frame rate of the motor
controller divided by the frame rate of the central
controller. Therefore, the frame rate of the motor controller
18 must be very close to an integer multiple of the frame rate

25 of the central controller 12.
        The moving average approach conditions the stair step
command signal 20 of the central controller 12 as illustrated
in Fig. 4. In this example, the frame rate of the central
controller was 100 frames per second, and the frame rate of

30 the motor controller was 800 frames per second. Applying the
moving average approach of Fig. 2. to the command signal 20
resulted in the smooth waveform 22.
        In another embodiment of the present invention as shown

in Fig. 5, conditioning of the command signal is accomplished through the use of a slewer-filter approach. This approach will be hereinafter referred to as the slewer-filter approach. In this embodiment, conditioning of the command signal is

5   accomplished through extrapolation of the command signal over a plurality of frames using a first order hold 24 and first order filter 26 combination. As with the moving average approach, this approach is preferably implemented in software residing on the motor controller 18. However, it can be

10   appreciated that it can be implemented in software residing on other devices of the control system or in hardware. In one embodiment, a first order filter is used with a slewer ranging between $100Hz$ to $800Hz$. The filter frequency is selected to attenuate the high frequency gain increase introduced by the

15   first order hold. A 17 Hz filter fulfills this criteria in this embodiment. It can be appreciated, however, that other criteria for selecting the filter frequency or higher order filters may be used depending on the dynamic characteristics of the system and/or the computational throughput capabilities

20   of the motor control electronics.

The first order hold is a linear extrapolation using the last two commands from the central controller with the starting point of the linear extrapolation being the most recent command. It is calculated as follows:

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$$\{C_c + T^* (C_c - C_{c-1})/ \Delta t_c \}$$

wherein T = the time from the most recent command from the central controller, updated at the motor controller frame rate;

Δt_c = the time between frames of the central controller;

30   C_c = the most recent command from the central controller; and

C_{c-1} = the previous command from the central controller.

The slewer-filter approach adjusts the command signal as illustrated in Fig. 5. Specifically, the command signal 28 from the central controller is conditioned by the first order

5   hold as reflected by signal 31 and then filtered, resulting in the smoothed signal 32. The break point of the first order filter is preferably selected to negate the high frequency gain increase introduced by the extrapolation of the first order hold, thus maintaining near unity gain across the

10   frequency range of the motion control system as illustrated in Figure 8b. A graph of the gain without the use of a filter is shown in Fig. 8a. Unlike the moving average method, this method is applicable to motion control systems where the motor controller frame rate is not an integer multiple of the

15   central controller frame rate. This flexibility, however, requires more complex software and improved numerical precision to implement.

As shown in Figs. 4 and 5, the signals 22 and 32 conditioned under the moving average approach and the slewer-

20   filter approach, respectively, show only slight differences in amplitude. The slewer-filter approach shows a slightly higher phase lag than the moving average approach, but this phase lag is no more than the zero order hold response of the control system without the slewer-filter approach. Moreover, this

25   phase lag can be tuned by adjusting the filter frequency to trade off gain and phase to best meet the dynamic response and stability requirements of the overall control system.

Figure 6 illustrates the reduction in heat generation resulting from use of the present invention. Specifically, it

30   compares the heat load generated by math models of a conceptual electro-mechanical actuator under a typical operation cycle. Graph 36 represents the heat load generated

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by the actuator without using either the moving average or slewer-filter approach. Graph 38 represents the heat load generated by the actuator using the moving average or slewer-filter approach. Figure 7 compares the corresponding

5   comparative heat loads at the motor controller 18 for the same actuator of Figure 6.

This heat load data was input into a detailed thermal model of an aircraft and it was demonstrated that actuator and motor controller temperatures could be reduced significantly

10 as shown in the following tables:

	No Filter		8 Point Average Filter	
	Peak Temp. (°F)	Peak Temp. (°C)	Peak Temp. (°F)	Peak Temp. (°C)
Actuator				
Winding	409.4	209.7	298.5	148.1
Stator	343.0	172.8	276.3	135.7
Housing	274.9	135.0	235.8	113.2

	No Filter		8 Point Average Filter	
	Peak Temp. (°F)	Peak Temp. (°C)	Peak Temp. (°F)	Peak Temp. (°C)
ACU				
IGBT Module	279.4	137.4	244.7	118.2
Chassis	219.6	104.2	204.8	96.0

By minimizing the need for additional cooling systems,

15 this invention reduces the weight of products in which it is incorporated. In an aircraft, weight savings typically result in significant operational and support cost savings. Most importantly, however, mathematical simulations have shown that the present invention can significantly reduce waste energy

20 and heat generation, in some cases by more than thirty percent (30%).

While the present invention has been described by reference to specific embodiments and specific uses, it should be understood that other configurations and arrangements could

25 be constructed, and different uses could be made, without

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departing from the scope of the invention as set forth in the following claims. In particular, the invention can used in any high response application.

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